Journal of Biomechanics 157 (2023) 111737

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Reactive responses of the arms increase the Margins of Stability and decrease center of mass dynamics during a slip perturbation

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ARTICLE INFO

Keywords:
Slip
Center of mass (CoM)
Arms
Margins of stability (MoS)
Balance
Falls

ABSTRACT

Although reactive arm motions are important in recovering from a slip event, the biomechanical influences of upper extremity motions during slipping are not clear. The purpose of the current study was to determine whether reactive arm motions during slip recovery leads to increased margins of stability (MoS), and decreased center of mass (CoM) velocity and excursion. Thirty-two participants were randomized into 2 conditions: arms free and arms constrained. Participants traversed a 10-meter walkway and were exposed to an unexpected slip while wearing a protective harness. Anterior-posterior and medial–lateral MoS, as well as the CoM excursion and velocity during the slip perturbation was quantified using a three-dimensional motion capture system. In the frontal plane, individuals with their arms unconstrained demonstrated greater MoS (0.06 ± 0.03 vs −0.01 ± 0.02 m, $p < 0.01$), decreased CoM excursion (0.05 ± 0.02 vs 0.08 ± 0.01 m, $p = 0.015$), and a reduced CoM velocity (0.07 ± 0.03 vs. 0.14 ± 0.02 m/s, $p < 0.01$) compared to individuals with their arms constrained. In the sagittal plane, individuals with their arms unconstrained demonstrated, decreased CoM excursion (0.83 ± 0.13 vs 1.14 ± 0.20 m, $p < 0.01$) reduced CoM velocity (1.71 ± 0.08 vs. 1.79 ± 0.07 m/s, $p = 0.02$), but no differences in margins of stability (0.89 ± 0.13 vs 0.94 ± 0.10 m, $p = 0.32$). Our findings demonstrate that arm motions during a slip perturbation act to restore balance by minimizing displacement and velocity of the body CoM during a slip event in the frontal plane.

1. Introduction

Successful recovery from a slip event involves coordinated corrective responses of the upper and lower extremities (Cham and Redfern, 2001; Marigold et al., 2003). With respect to the upper extremities, previous research has shown that the arms exhibit bilateral flexion in the sagittal plane (Marigold et al., 2003; Merrill et al., 2017; Troy et al., 2009) and abduction of the arm contralateral to the slipping foot (Lee-Confer et al., 2022a). Furthermore, Lee-Confer and others (2022b) revealed that the reactive motion of the arm contralateral to the slipping foot is most important in regaining balance once a slip has been initiated.

Although reactive arm motions are important in recovering from a slip event, the underlying biomechanical mechanisms are not entirely clear. With respect to sagittal plane motions during slipping, the arms have been postulated to shift the center of mass anteriorly to counter a backwards loss of balance induced from a slip perturbation (Marigold et al., 2003). In addition, sagittal plane arm motions during slipping have been shown to reduce the trunk extension velocity (Troy et al., 2009). In contrast to sagittal plane arm motions during slipping, little is known about how frontal plane arm motions aid in recovery from a slip. This is important given that the largest arm motion during slipping occurs in the frontal plane of the arm contralateral to the slipping foot (Lee-Confer et al., 2022a).

One construct that can be used to understand how arm responses aid in the recovery of a slip event is the Margin of Stability (MoS). The MoS represents the dynamic relationship between the body center of mass (CoM) and the base of support in the medio-lateral and antero-posterior directions (Golyski et al., 2022; Hof et al., 2005; Watson et al., 2021; Young et al., 2012). When a slip occurs during walking, the body CoM is posterior and medial to the slipping foot and anterior and medial to the trailing foot. During a slip, the CoM shifts posteriorly and laterally with respect to the leading limb, reducing the MoS and increasing the risk of

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https://doi.org/10.1016/j.jbiomech.2023.111737
Accepted 21 July 2023
Available online 22 July 2023

losing balance. To limit the reduction in the MoS and improve the chance of recovery, the excursion and velocity of the body CoM needs to be reduced in the posterior and lateral directions. Since the arms represent approximately 10% of the total body mass (Winter, 2009), reactive motions during a slip incident could act to increase the MoS by reducing CoM excursion and velocity in both the sagittal and frontal planes.

Using the MoS construct, the purpose of the current study was to determine how use of the arms aids in the recovery of balance during a slip event. To accomplish the aim, we compared MoS, CoM velocity and CoM excursion between persons who slipped with the arms unconstrained and with the arms constrained. It was hypothesized that the individuals with their arms free would demonstrate significantly greater MoS, and significantly less peak CoM velocity and excursion in both the frontal and sagittal planes compared to the individuals with their arms constrained.

2. Methods

2.1. Participants

Thirty-two healthy individuals between the ages of 21 and 35 participated in this study (13 males and 19 females). Prior to participation, volunteers were informed of the nature of the study, and signed a written informed consent form approved by the University of Southern California Health Science Campus Institutional Review Board. After providing informed consent, participants completed a medical questionnaire to screen for possible conditions that could jeopardize their safety by participating in this study. Specifically, individuals were excluded from participation if they reported any of the following: neurological or orthopedic conditions that would affect gait, current muscle strains or joint sprains, recent bone fractures, previous back injuries, or individuals who had the potential to be pregnant.

2.2. Instrumentation

All gait trials were conducted on a 10-meter walkway. A Teflon coated floor tile (California Technical Plating, San Fernando, CA, US) was imbedded into the walkway, secured on top of an AMTI force plate (Model OR6-6 1000, Advanced Mechanical Technology, Inc., Watertown, MA) and camouflaged such that the coloring of the tile matched the non-teflon tiles. Mineral oil was placed on the tile to reduce the coefficient of friction to induce slipping (see below for details).

Three-dimensional motion analysis was performed using an 11-camera motion analysis system (Oqus 5 series, Qualisys, Gothenburg, Sweden) collecting at 150 Hz. 76 reflective markers were placed over specific anatomical locations and used to quantify upper and lower extremity kinematics. To prevent falls during testing, a fall-arresting body harness (Miller Model 550–64, Dalloz Fall Protection, Franklin, PA, USA) secured with an 8 mm climbing rope was attached to an overheard low-friction trolley. An Omega S-beam load cell (Omega Engineering Inc., Norwalk, CT, US) connected the climbing rope to the trolley system and was used to measure the amount of supported bodyweight during the slip perturbation trials. To control for the potential influence of footwear on slip severity, participants were fitted with a pair of oxford dress shoes with a standard rubber outer sole (Bates Footwear, Richmond, IN, US).

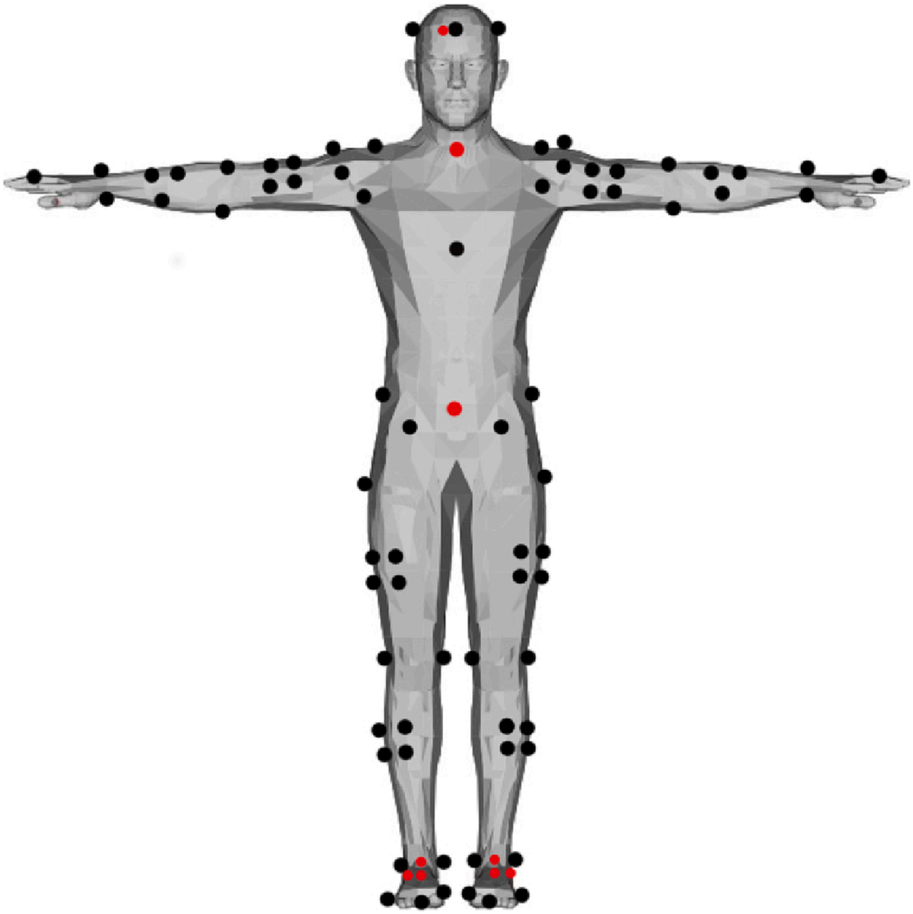

Fig. 1. A schematic of the full-body marker set. Black markers indicate markers visible from an anterior view. Red markers indicate markers on the posterior side of the body. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Procedures

Prior to testing, participants were fit to the adjustable fall arresting harness. The safety harness was adjusted to a height where a participant's hip would not drop below 35% of their height (Yang and Pai, 2011). Participants were then instrumented with a full body marker set (Fig. 1). Reflective spherical markers were placed on the L5S1, Xyphoid Process, and C7, and bilaterally on the: second toe, fifth metatarsal head, first metatarsal head, lateral and medial malleolus, lateral and medial epicondyles of the femur, greater trochanter, anterior superior iliac spine, iliac crest, acromioclavicular joint, anterior and posterior glenohumeral joint, greater tubercle, lateral and medial epicondyle of the humerus, radial and ulnar styloid processes, and the third metacarpal head. Additionally, a headband fitted with four markers were used to track the head, and marker tracking clusters were placed bilaterally on the: heel, shank, thigh, upper arm and forearm.

Participants were randomly assigned into one of two potential arm constraint conditions: both arms free (n = 16) or both arms bound (n = 16) (Table 1). Participants in the arms bound group had an adjustable polypropylene strap wrapped around their thorax and upper arm, approximately 2–3 in. above the elbow (Fig. 2). Additionally, both wrists were securely fastened to the harness through padded wrist restraints. The lighting in the laboratory was dimmed so the light measurement over the Teflon surface was four foot-candles. This level of lighting ensured that the participants had ample lighting to walk safely while also providing additional concealment of the Teflon surface. Participants were permitted 10 practice walking trials to adjust to the harness system and dimmed lighting conditions and to achieve a consistent walking speed of 1.35–1.5 m/s as determined via photoelectric switch. The participants' starting location was adjusted between each practice trial so their right foot would strike the concealed Teflon tile to initiate the slip. Participants were unaware of the location of the Teflon tile to avoid anticipatory gait changes to a potential perturbation (Heiden et al., 2006; Siegmund et al., 2006).

Following the practice trials, force plate data were obtained during four non-slip walking trials. Between each trial, participants faced away from the walkway for one minute such that they would be uncertain as to the trial in which a slip would occur. Loud music was played during testing to act as an additional distraction. The mineral oil contaminate was placed on the Teflon tile after obtaining the four non-slip walking trials.

Following the slip trial, participants were asked if they had anticipated the slip or if they had seen the contaminant following the slip trial. Any anticipation or observation of the contaminant resulted in the individual being excluded from the study. All participants slipped on their right foot and were only exposed to one slip for the entire study.

2.4. Data analysis

Slip outcomes were classified as a fall if participants required more than 30% support of their body weight after slip initiation (Yang and Pai, 2011). Only participants that recovered from a slip were analyzed for this study. Kinematic data were filtered using a second order, 6 Hz, low pass Butterworth filter with zero-lag compensation.

Fifteen body segments (head, pelvis, thorax, and bilateral feet, shank, thigh, upper arm, forearm, and hand) were created through a custom designed model template using Visual 3D software (Version 5, C-Motion, Inc., Germantown, MD, USA). Individual marker data, trunk kinematics and whole-body CoM were exported for subsequent analysis in Matlab (Mathworks, Natick, MA, USA). For all variables, the start of the analysis was defined at the time point of slip initiation and the end of the analysis was defined at the time point when the trunk reached maximal right trunk lean. To determine slip initiation, the integrated sum of the vertical force data during the four non-slip trials were calculated and averaged. The onset of the slip was defined as the time point when the integrated-sum of the vertical force during the slip trial deviated more than two standard deviations from the averaged integrated-sum of the vertical force of the non-slip trials. (Lee-Confer et al., 2022a). Maximal right trunk lean was selected as the final time point as maximal right trunk lean would serve as the furthermost position of the upper body in the lateral direction during a slip perturbation.

Table 1
Participant characteristics for the two arm constraint conditions.

	Arms Constrained (N = 16)	Arms Free (N = 16)	P = value
Age (years)	26.1 ± 2.7	25.2 ± 1.2	p = 0.23
Height (m)	1.67 ± 0.1	1.72 ± 0.1	p = 0.16
Weight (kg)	65.5 ± 11.7	66.2 ± 9.8	p = 0.86
Shoe Size (EU)	41.9 ± 2.4	41.7 ± 1.5	p = 0.78
Sex (M/F)	6/10	6/10	p = 0.99

Fig. 2. Arm constraint positioning used in the current study with both arms constrained (left) and no arms constrained (right).

We computed MoS in the AP and ML directions using methodology reported previously (Aprigliano et al., 2015; Arora et al., 2020; Hof et al., 2005; Martelli et al., 2017; Siragy et al., 2021; Sivakumaran et al., 2018). The edge of the base of support in the frontal plane was defined by the right 5th metatarsal head marker. The posterior edge of the base of support in the sagittal plane was defined as the left posterior heel marker as it represented the most posterior position of the foot of the trailing leg. The MoS in the frontal plane was calculated by taking the medio-lateral position of the right 5th metatarsal head and subtracting the medio-lateral position of the extrapolated CoM (Fig. 3). The extrapolated CoM was adapted from previous research (Hof et al., 2005). The extrapolated center of mass (XCoM) was calculated as follows:

$$\mathrm{XCoM} = \mathrm{x} + \frac{\dot{\mathrm{x}}}{\omega_0}$$

where x was the CoM position, $\dot{x}$ was the CoM velocity and

$$\omega_0 = \sqrt{\frac{g}{l}}$$

where $g = 9.81\ \mathrm{m/s^2}$ was the gravitational constant and l was the equivalent pendulum length defined in this study as the distance between the lateral heel marker to the greater trochanter on the ipsilateral limb.

MoS in the sagittal plane was calculated by subtracting the position of the left posterior heel marker from the fore-aft position of the extrapolated CoM (Fig. 3). Values nearing zero for the MoS are indicative of a higher risk of falling as the extrapolated CoM is reaching the limits of the base of support. We computed CoM excursion relative to the

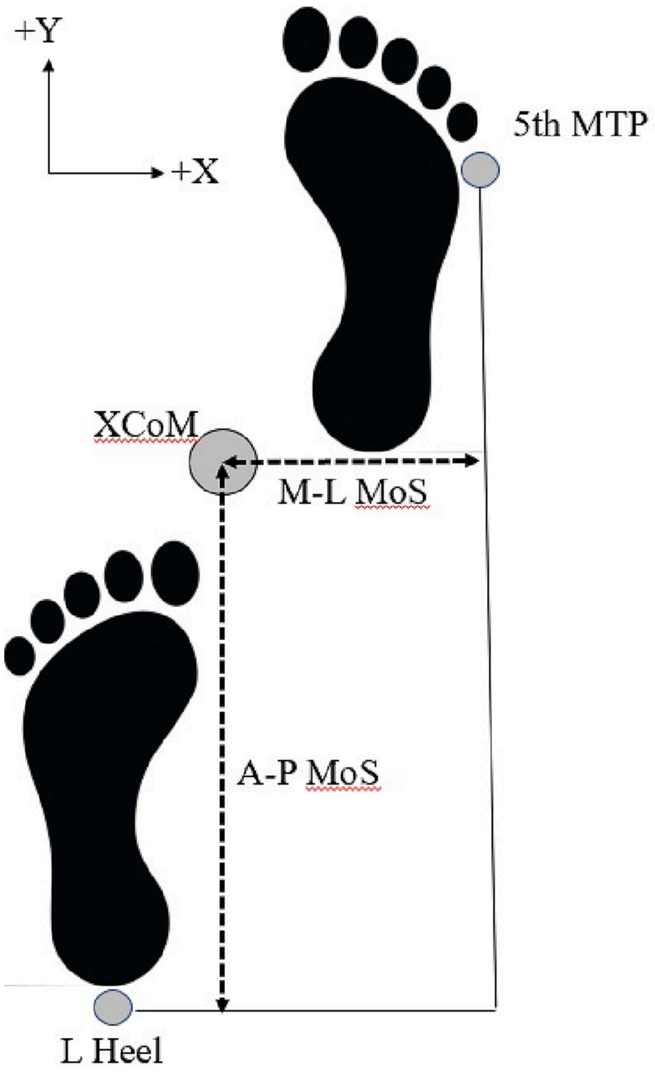

Fig. 3. Schematic illustrating the M−L and A-P Margins of Stability (MoS) calculation.

laboratory coordinate system with the anterior (AP) and right (ML) assigned as positive directions (Fig. 3). Peak CoM frontal plane excursion was calculated by taking the rightmost position of the CoM at maximal right trunk lean and subtracting that from the medio-lateral CoM position at slip initiation. Peak CoM velocity in the frontal plane was obtained from the derivative of the medio-lateral CoM position between slip initiation and maximal right trunk lean (Fig. 4). Peak CoM excursion in the sagittal plane was calculated by taking the greatest antero-posterior position of the CoM between slip initiation and maximal right trunk lean, and subtracting that from the initial antero-posterior CoM position at the time of slip initiation. Peak CoM velocity in the sagittal plane was obtained from the derivative of the antero-posterior CoM position between slip initiation and maximal right trunk lean.

2.5. *Statistical analysis*

A Mann-Whitney nonparametric test was used to compare minimal MoS, peak CoM velocity and CoM excursion between the arms free and arms constrained groups. This analysis was repeated for both the frontal and sagittal planes. Analyses were performed using SPSS 16.0 statistical software (SPSS, Chicago, IL, USA) and significance levels were set at $p < 0.05$.

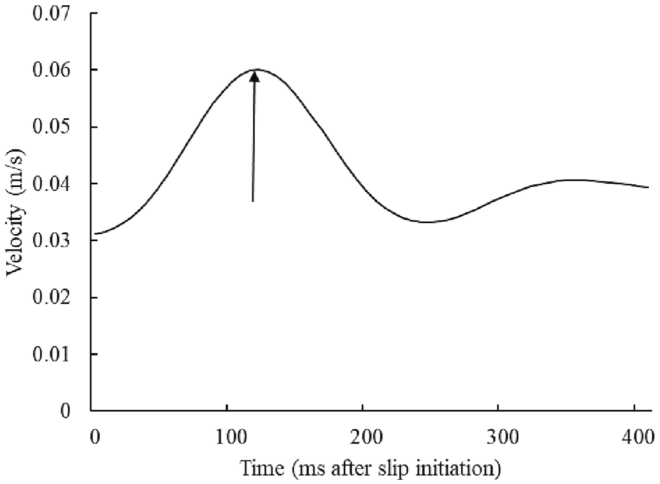

Fig. 4. Center of mass velocity of a representative slip trial from a single participant. The black arrow indicates the peak center of mass velocity.

3. Results

In the arms free group, 13 of the 16 participants recovered from the slip perturbation while only 6 of the 16 participants in the arms constrained group recovered. As such, the data below (mean ± SD) represent a comparison of 13 individuals in the arm free group and 6 in the arm constrained group.

The individuals who recovered with their arms free had a significantly larger MoS in the frontal plane compared to the individuals who recovered with their arms constrained (0.06 ± 0.03 m vs. −0.01 ± 0.02 m, $p = 0.003$, Fig. 5 & Fig. 6). In contrast, there was no significant difference in the sagittal plane MoS between the arms free and arms bound groups (0.89 ± 0.13 m vs. 0.94 ± 0.10 m respectively, $p = 0.32$, Fig. 5 & Fig. 6).

The individuals who recovered with their arms free had a significantly reduced CoM excursion in the frontal plane compared to the individuals who recovered with their arms bound (0.05 ± 0.02 m vs. 0.08 ± 0.01 m, $p = 0.016$, Fig. 7). Similarly, the CoM excursion in the sagittal plane was significantly less in the individuals who recovered with their arms free compared to those who recovered with the arms bound (0.83 ± 0.13 m vs. 1.14 ± 0.20 m, $p = 0.001$, Fig. 7). Compared to individuals who recovered with the arms bound, those who recovered with their arms free had a significantly reduced CoM velocity in the frontal plane (0.07 ± 0.03 m/s vs. 0.14 ± 0.02 m/s, $p = 0.002$, Fig. 8) and sagittal plane (1.71 ± 0.08 m/s vs. 1.79 ± 0.07 m/s, $p = 0.027$, Fig. 8).

4. Discussion

The purpose of the current study was to quantify the biomechanical contributions of the upper extremities in regaining balance during a slip perturbation. In partial support of our hypothesis, the individuals who recovered with their arms free demonstrated a significantly increased MoS than those with their arms constrained. However, this difference was only observed in the frontal plane. Increased MoS in the frontal plane in the arms free group was achieved by limiting CoM velocity and excursion.

The findings of our study suggest that arm motions are useful for controlling the displacement of the CoM in the frontal plane. This finding is consistent with previous research from our group that found the contralateral arm to the slipping foot exhibited significantly more motion in the frontal plane (abduction) compared to the sagittal plane (flexion) (Lee-Confer et al., 2022a) Additionally, our findings are consistent with studies that have shown that contralateral arm abduction reduces the CoM excursion in individuals subjected to moving

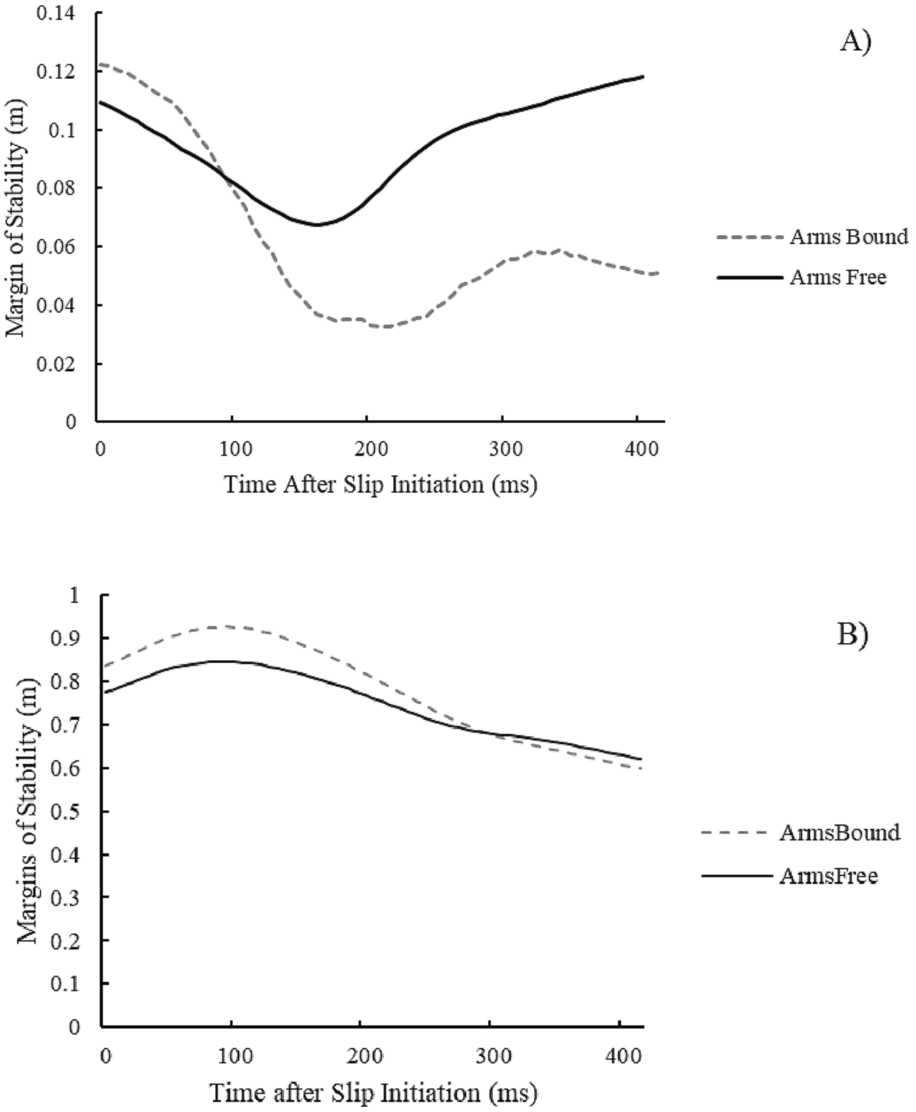

Fig. 5. A) Time series data for the Margins of Stability (m) for the arms free (n = 13) and the arms bound (n = 6) condition in the frontal plane. B) Time series data for the Margins of Stability (m) for the arms free (n = 13) and the arms bound (n = 6) condition in the sagittal plane. The solid black line represents the average Margin of Stability for the individuals with their arms free. The dashed gray line represents the average Margin of Stability for individuals with their arms constrained.

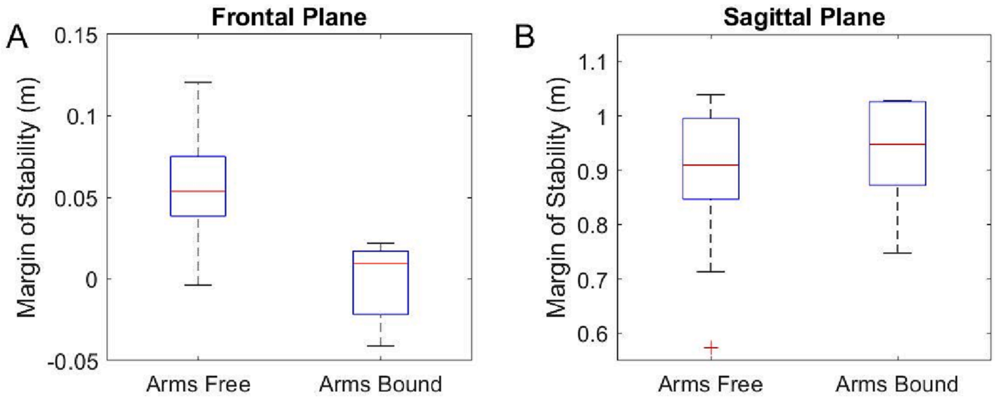

Fig. 6. Margins of Stability between the arms free (n = 13) and arms bound (n = 6) groups in the frontal (A) and sagittal (B) plane. The arms free condition exhibited a larger Margin of Stability in the frontal plane indicating an increase safety margin compared to the arms bound group. No differences were found in the sagittal plane. + denotes outlier. For both box plots, the horizontal red line indicates the median, the horizontal black lines indicate maximum and minimum values, and the horizontal portions of the blue box define the interquartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

platform perturbations (Grin et al., 2007). The greater MoS observed in the individuals who recovered with their arms free was the result of a significantly lower CoM velocity and lower CoM excursion in the medio-lateral direction. On average, these values were about half that of the arm constrained group. Our data suggest that frontal plane motion of the upper extremities is acting to reduce the CoM excursion and the CoM

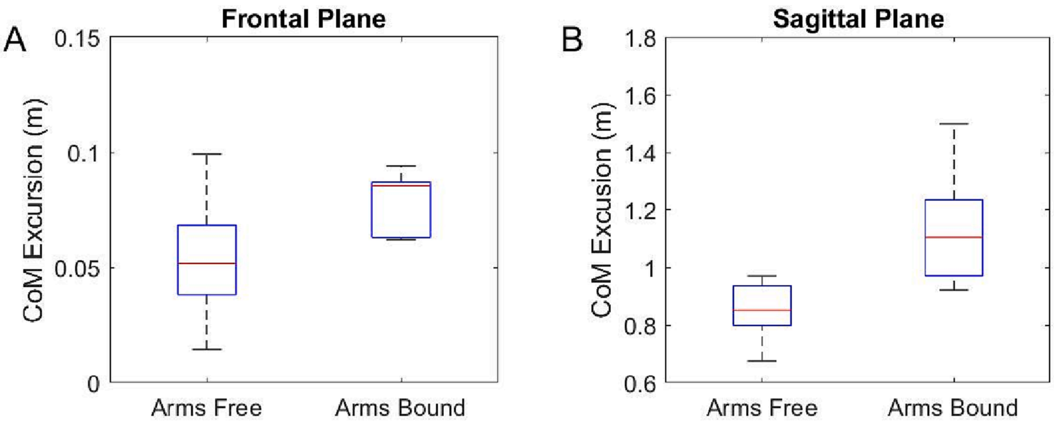

Fig. 7. Whole-body center of mass excursion between the arms free (n = 13) and arms bound (n = 6) groups in the frontal (A) and sagittal (B) plane. The arms free group exhibited significantly reduced center of mass excursions in the frontal and sagittal plane compared to the arms bound group. For both box plots, the horizontal red line indicates the median, the horizontal black lines indicate maximum and minimum values, and the horizontal portions of the blue box define the interquartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

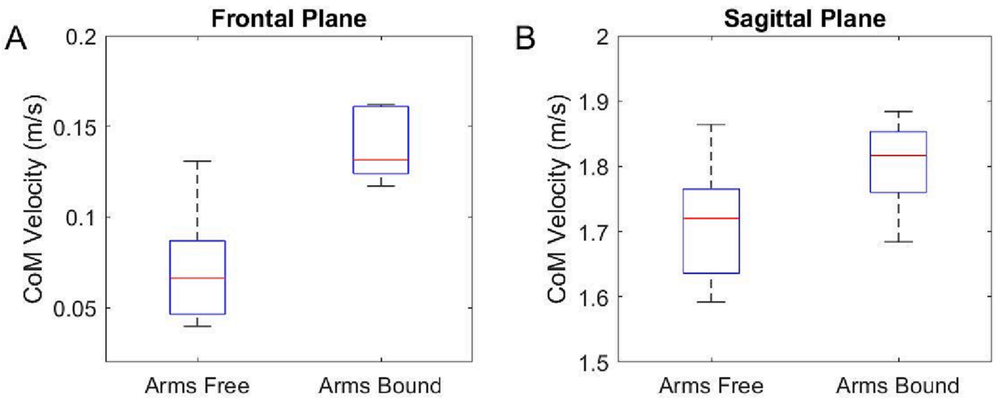

Fig. 8. Whole-body center of mass velocity between the arms free (n = 13) and arms bound (n = 6) groups in the frontal (A) and sagittal (B) plane. The arms free group exhibited significantly lower center of mass velocity directed in the ML and AP directions compared to the arms bound group. For both box plots, the horizontal red line indicates the median, the horizontal black lines indicate maximum and minimum values, and the horizontal portions of the blue box define the interquartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

velocity.

The potential influence of frontal plane arm motion on the MoS can be visualized in Fig. 8. As the individual slips on their right foot (with both arms free), the body begins to rotate towards the right (right trunk lean in the frontal plane). The right lateral flexion of the trunk observed in Fig. 9 is similar to what is described in other research that reports lateral disturbances during a slip incident (Allin et al., 2018; Rasmussen and Hunt, 2021; Smeesters et al., 2001). To counter the CoM excursion, it is possible that abduction of the contralateral arm to the slipping foot (left arm) would have the effect of minimizing CoM velocity and excursion to the right. This is aligned with the idea that the arms may assist in changing the orientation of the body into a position that reduces the likelihood of losing balance (Van Leeuwen et al., 2022).

Interestingly, there were no significant differences in the MoS between the arms free and arms bound group within the sagittal plane. This suggests that the ability to recover from a slip event is more dependent on the ability to maintain balance in the frontal plane. In previous studies, the arms were reported to perform bilateral flexion during a slip perturbation (Marigold et al., 2003; Troy et al., 2009). It was proposed that the bilateral flexion response acted to shift the CoM anteriorly in response to a slip perturbation and this premise was supported by the results of the current study. Given that reactive arm flexion in the sagittal plane has been reported to be about one-third of the motion in the frontal plane, (Lee-Confer et al., 2022a) suggests that the magnitude of motion was not sufficient to lower the MoS.

Despite the finding of no significant difference in MoS in the sagittal plane, center of mass excursion and the CoM velocity was significantly lower in individuals who recovered with their arms free compared to those with their arms constrained. This finding is counter intuitive as a lower CoM excursion and lower CoM velocity would be expected to contribute to a reduced MoS as the center of mass would be further posterior and closer to the BoS. However, when interpreting the results of the sagittal plane MoS, the position of the trail foot (i.e. base of support) needs to be considered. It is possible that the individuals with their arms constrained compensated by shifting their trailing foot (the non-perturbed foot) further anterior, as to reposition the base of the support under the center of mass.

The current study highlights the importance of arm motions in the recovery of balance during a slip perturbation. This was illustrated by the fact that a greater percentage of participants fell when the arms were constrained compared to the arms free group (62.5% vs. 18%, respectively) during the slip perturbation (Lee-Confer et al., 2022b**).** Furthermore, the arms are reported to reduce the angular momentum during a slip perturbation in the sagittal plane (Nazifi et al., 2020) and it is likely the arms have a similar effect in the frontal plane. The clinical implications of our findings are readily apparent as many fall prevention programs focus primarily on lower extremity strengthening and balance training (Karinkanta et al., 2010). However, a recent study demonstrated that upper extremity responses may be trained to exhibit shorter reaction times (Arnold et al., 2022). To date, no studies have investigated the efficacy of interventions that focus on strengthening/reactive training of the upper extremities. Upper extremity training could lead to a decrease in fall risk if individuals are able to effectively utilize the mechanical benefits of arm motions during a slip perturbation.

It is possible that observed difference in slip recovery between the arms free and arms bound conditions may have been influenced by

Fig. 9. An example of a participant experiencing a slip. As the slip is initiated, the body, thus the center of mass, shifts towards the perturbed foot (white solid arrow). The contralateral arm to the slipping foot actively performs abduction which opposes the lateral-directed center of mass (white dashed arrow) to effectively reduce center of mass excursion and velocity during a slip.

variations in gait kinematics that could impact slip potential and/or slip severity. To evaluate this possibility, we performed a post-hoc analysis of the peak utilized coefficient of friction (uCOF) between the arms free and arms bound group during the non-slip trials. The uCOF is calculated as the ratio of shear to vertical forces and has been shown to be a global indicator of slip probability (Burnfield & Powers, 2006). The peak uCOF during the non-slip walking trials did not differ between the two groups (0.194 ± 0.027 vs. 0.193 ± 0.026; $p = 0.92$) indicating that the two groups were similar in terms of slip potential.

A potential limitation of any laboratory-based slip study is the potential for anticipatory gait changes that may influence slip outcome. It has been established that individuals change their gait patterns and walk more “safely” when they are aware that they may encounter a perturbation (Heiden et al., 2006). A more protective gait could impact the results reported above and may not reflect the true arm responses or fall frequencies that might be observed if the slip perturbation occurred naturally in the environment (ie. wet floor, etc.). Another potential limitation to this study is the age of our study participants. This study only included younger and healthy adults, and as such, our results cannot be generalized to other populations who may be a higher risk of falling (i.e. older adults).

5. Summary

Upper extremity responses during a slip response significantly increase the MoS and reduce the CoM velocity and excursion, but only in the frontal plane. Within the sagittal plane, reduced CoM excursion and velocity was evident in the arms free group and was not sufficient to alter the MoS. The arm motions observed during a slip, particularly in the frontal plane, result in individuals reducing their likelihood of falling by modulating center of mass kinematics. This finding provides a more comprehensive view of the role of the upper extremities in recovering from a slip perturbation while walking.

CRediT authorship contribution statement

Jonathan S. Lee-Confer: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James M. Finley:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Kornelia Kulig:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Christopher M. Powers:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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